

REDUNDANCY FOR ELECTRIC MOTORS  
IN SPACECRAFT APPLICATIONS

Robert J. Smith and Alastair R. Flew\*

This paper identifies the parts of electric motors which should be duplicated in order to provide maximum reliability in spacecraft applications. The paper describes various common types of redundancy and gives the advantages and disadvantages of each. The principal types are illustrated by reference to specific examples. For each example, constructional details, basic performance data and failure modes are described, together with a discussion of the suitability of particular redundancy techniques to motor types.

## INTRODUCTION

The question of redundancy in electric motors for space applications is fascinating if nothing else because of the large number of ways in which redundancy can be achieved. This paper will describe some of these techniques, all the data being from real applications.

It will be noted that the redundancy techniques described are not restricted solely to one type of electric motor. To illustrate this point examples are given of both Stepping motor and D.C. motor applications using the same redundancy technique. The redundancy techniques described have been used in many different applications including solar array drive mechanisms, deployment mechanisms, antenna pointing mechanisms and motorised hinges.

There is of course no universally accepted or right approach to the question of redundancy in electric motors. The decision on which technique should be used is usually a compromise between reliability, criticality of application, mass, cost, physical size, performance and many other factors, not least of which is the personal preference of the mechanism designer.

Despite, however, these apparent problems we have attempted to draw comparisons between the various methods available and these appear in the form of selection charts shown in Tables 1 and 2. We hope this will be useful for future reference and we certainly expect it to generate further discussion on what we find to be an interesting aspect of electric motor design for space application.

---

\*Moore Reed and Company Limited, Andover, England.

## TYPES OF REDUNDANCY

There are basically five different types of redundancy which are applicable to electric motors. These range from total system duplication to zero redundancy and are discussed in detail below.

For clarity, that part of the system which is normally energised under no-fault conditions is referred to as the Prime system and the back-up system (normally unpowered) is referred to as the Redundant system. In the event of a failure in the Prime system, it is necessary to:

- a) de-energise the Prime system
- b) energise the Redundant system.

Because any such failure represents a major event in the life of a motor system, the changeover from Prime to Redundant system is not normally automatic but is instead initiated by ground commands. In this way due consideration may be given to the mode of operation which caused the Prime system to fail and a decision made as to whether continuing operation in this mode could lead to a similar failure of the Redundant system.

### Type 1 Redundancy - Two motors geared to a common shaft

Under this arrangement, a pair of similar, non-redundant motors are coupled to the driven shaft, often by means of reduction gears. One motor is normally energised and the other (the Redundant motor) is de-energised and normally back-driven by the Prime motor.

It is therefore important that either motor operating alone is capable of driving the load and back-driving the Redundant motor. Effects such as the bearing friction and magnetic detent torque of the Redundant motor will be magnified by the gear ratio, whilst rotor inertia will be reflected as the square of the gear ratio.

Under fault conditions, if the failure mode is open-circuit, operations may continue using the Redundant motor with no decrease in overall system performance. If, however, the failure mode is a short-circuit, the retarding torque of the failed motor will increase - possibly substantially - depending on the type of motor and the severity of the fault.

In order to overcome these problems both motors must be larger and more powerful than if a non-redundant system were used. The gear mechanism must be strong enough to withstand operation in the presence of maximum retarding torque due to a failed motor.

If high positional accuracy of the driven shaft is required, backlash in the reduction gearing may cause difficulties when changing from Prime to Redundant motors.

### Type 2 Redundancy - Two motors and differential gearbox

Using this system, the speed of the output shaft of the gearbox is proportional to the difference in speed of the two input shafts. Drive can thus be transmitted from either motor whilst the other remains stationary. The differential unit has internal losses which represent a retarding torque and the motors must each be capable of overcoming this in addition to the load torque. As it is not necessary to be able to back-drive a failed motor, the motors need not be as large and powerful as if Type 1 redundancy were employed.

Type 2 redundancy therefore gives good protection against both open-circuit and short-circuit failure modes. Its principal disadvantage lies in the mass and complexity of the differential unit, which is in itself a non-redundant element.

### Type 3 Redundancy - Tandem motor

Under this type of redundancy, two motors are effectively combined into one unit, that is, two stator assemblies in a common housing, and two corresponding rotor assemblies on a common shaft. Fig.1 shows this type of redundancy applied to a frameless Stepping motor. The Prime and Redundant parts of the motor are electrically and mechanically isolated, but the additional detent torque of the Redundant system acts to reduce the overall output torque of the Prime system. As with Type 1 redundancy, full protection is given against open-circuit failures, but any form of short-circuit failure results in increased retarding torque of the affected system. However, with Prime and Redundant elements mounted on a common shaft, there is no magnification factor and any retarding torque is transmitted on a 1:1 basis.

Each half of a tandem motor can, therefore, be smaller than an equivalent non-redundant motor under Type 1 redundancy. Mass will also be less than for two separate motors as only one set of bearings and end frames is required.

One obvious disadvantage of the tandem motor is its extra length and this type of redundancy should not be considered unless the basic rotor and stator elements are themselves short and compact. For instance, cylindrical-armature D.C. motors do not lend themselves to the tandem-motor configuration, whereas "pancake" style motors are well suited. Even so, it may prove necessary to provide an auxiliary rear support to the motor if it is required to survive in a severe vibration environment. On machines with small radial air-gaps (e.g. Stepping motors) it is also necessary to ensure that the shaft is sufficiently rigid and well supported to avoid rotor-stator contact.

#### Type 4 Redundancy - Dual-wound Motor

Only the windings, electrical connections and leadwires are duplicated with Dual-wound redundancy. All the other parts remain as for a non-redundant motor. However, since it is invariably the windings and/or lead connections where the probability of failure is highest, this type of redundancy is entirely acceptable and valid. The Prime and Redundant windings are normally separated from each other by Mylar or Melinex insulators. Fig. 3 shows the technique applied to a housed Stepping Motor. Because only half the normal slot area is available for each winding, the performance of a dual-wound motor is inevitably less than for a comparable non-redundant motor operating under similar conditions. Detent torque and mass are approximately the same as for a non-redundant motor.

On certain types of motor it is difficult to achieve complete physical separation between Prime and Redundant windings. This is particularly true of brush D.C. motors where there are a large number of coil end-to-commutator connections which tend to overlap or cross one another. Also, because the Prime and Redundant windings are in closer proximity than with other types of redundancy, there is a possibility of thermal interaction between the two windings.

With the Prime and Redundant windings sharing a common magnetic circuit, a degree of transformer action occurs when alternating current flows in one winding. With a short-circuit fault on one winding, the machine behaves like a transformer on load and the input current rises to supply the secondary current. This current, flowing in the failed winding, also creates a retarding torque, so the overall output torque of the motor is degraded. For obvious reasons, the effect is only apparent in Stepping motors operating at high stepping rates; at low step rates, or when using D.C. motors, the effect is negligible.

Like the other types of redundancy so far discussed, dual-winding gives complete protection against open-circuit failure modes.

#### Type 5 Redundancy - No duplication

Although not strictly a redundancy method, zero duplication must at least be considered as an option. From the foregoing, it might be inferred that wound electrical components have inherently poor reliability. However, this is not the case and the main reason for providing redundancy is that electrical actuators are often used in highly critical applications where a failure, however remote the possibility, could have a catastrophic impact on the success of the mission. This is particularly true of mechanisms designed for continuous operation of up to 10 years duration on geosynchronous spacecraft. However, there are many applications (such as payload experiments) where non-redundant motors are completely acceptable. Motors can be designed so that known failure modes are reduced or eliminated.

For instance, the use of ultra-fine winding conductors can generally be avoided, as can the common practice of pressing a winding to form it into a more compact shape. Performing solder joints to space-approved standard and minutely examining joints (before and after insulation) for compliance with these standards, are further examples of how the quality of manufactured items is maintained. During testing, exposure of all Flight units to acceptance-level vibration and subsequent electrical testing, further ensures that the motors are as free as possible from any design or manufacturing defect.

So, by applying an appropriate level of product assurance, the reliability of even a non-redundant motor can be significantly improved over that of a commercial-standard motor.

#### FAILURE MODES

Potential failure modes applicable to most types of electric motor are:

- Bearing Failure
- Air gap contamination
- Demagnetisation
- Open-Circuits
- Short-Circuits
- Insulation breakdown to chassis.

In addition, there are generally other failure modes specific to the particular motor under consideration. These invariably relate to the mechanical configuration of the motor and must be considered on an individual basis. The above principal failure modes are now discussed under separate headings.

##### Bearing Failure

The various failure modes of ball bearings are well documented and are not within the scope of this paper. However, ball bearings are invariably non-redundant components and any increase in bearing friction will reduce the overall torque capability of the motor. Only Type 2 redundancy gives protection against motor failures of this nature.

##### Air gap contamination

For obvious reasons, motors having small air gaps (such as Stepping motors) are more susceptible to air gap contamination than other types. Fortunately, by adopting stringent cleaning procedures at component level and performing final assembly operations under clean room conditions, contamination from sources within the motor can be made to be an extremely unlikely event.

Because most motors used in spacecraft applications employ permanent magnets in either the stator or the rotor, any ferrous debris which does occur inside the motor (or which is subsequently introduced into the motor) will tend to be attracted into the air gap region. There is thus an obvious possibility of increased frictional torque or even rotor jamming. As with bearing failure, only Type 2 redundancy gives protection against this type of motor failure.

### Demagnetisation

The performance of most Permanent Magnet materials is subject to both reversible and irreversible changes. Reversible changes normally occur as a result of high or low temperature operation, with the highest flux density occurring at low temperatures and vice versa. Normal magnet performance is restored on return to room temperature. This normally affects both Prime and Redundant systems equally and should be considered as a motor characteristic rather than a failure mode as such.

Irreversible demagnetisation is a more severe effect because it can only be restored by remagnetisation. It can happen if a motor is over-driven by, for example, operating on too high a supply voltage, or by instantaneously reversing the polarity of the supply to a D.C. motor. Certain magnetic materials (e.g. ferrites) are more susceptible to irreversible demagnetisation at low temperatures.

The effect of irreversible demagnetisation on a motor is to reduce its output torque for a given supply current and (in the case of a D.C. motor) to increase the gradient of the speed versus torque characteristic. This type of failure can be accommodated by switching to the Redundant system where Redundancy Types 1, 2 or 3 are used. Type 4 redundancy (dual-winding) does not give protection against this failure mode because both Prime and Redundant windings share a common magnetic circuit.

Provided the specified power supplies are not exceeded, a correctly designed motor should be capable of operating at all points within its specified temperature range, under any load conditions, without irreversible demagnetisation.

### Open Circuits

Open-circuits can be induced by vibration or by adverse thermal conditions, or by a combination of both. Under hard vacuum conditions, it is often difficult to provide adequate paths for thermal power dissipation, particularly when the power is supplied to the rotating component such as a D.C. motor armature. Localised temperature rises can, therefore, be quite significant. If the motor is also required to operate under high ambient temperature conditions, there is a possibility of solder joint failure if

temperatures exceed about 180°C. The integrity of the various insulation systems cannot normally be assured above this temperature. Motor operational constraints are often introduced for this reason and it is important that these are observed. The effect of an open-circuit is misstepping in the case of a Stepping motor, and reduced torque and speed in the case of a D.C. motor.

There are two types of open-circuit failure specific to brush D.C. motors. One is brush failure: a brush which fails to make contact with a commutator, or a broken brush connector, can result in total motor failure. The second type of failure is a broken conductor-to-commutator joint. This failure, whilst not so severe, can cause a significant decrease in performance.

There is also a range of drive, wiring, and connector faults which, occurring externally to the motor, can give the same effect as an open-circuit within the motor.

All the open-circuit failure modes above can be overcome without penalty by switching to the Redundant part of the system, irrespective of the type of redundancy used.

#### Short-circuits

The worst case short-circuit is a terminal-to-terminal short which in most cases can only occur due to a fault external to the motor. Most internal short-circuits originate in the same way as for open-circuits. It is possible for two open-circuits to combine to form a short-circuit. The short-circuit failure is always more severe than an open-circuit in that motor performance, even when operating on the Redundant winding, is less than when operating under no-fault conditions on the Prime winding. Only Type 2 redundancy offers the possibility of full protection against this sort of failure.

#### Insulation breakdown to chassis

This can be thermally or vibration induced, as for open-circuits or, in machines fitted with brushes, insulation breakdown can occur as a result of brush debris accumulation. Motors are normally manufactured so that all electrically active components are fully isolated from the structural parts of the machine. Because of this, a single insulation breakdown is unlikely to have any noticeable effect on motor performance, unless it affects the operation of the drive circuits. Two insulation breakdowns in the same winding will, however, produce a short-circuit. If the electronic drive components are configured such that even a single insulation breakdown can cause fault current to flow in the winding, then this will also produce a short-circuit.

## RECENT EXAMPLES OF MOTORS HAVING REDUNDANCY

### Tandem Stepping Motor

The motor to be described is a frameless, size 23, 2 phase,  $1.8^\circ$  step motor designed for operation on bipolar drives in full step or ministep mode. The motor was designed for continuous running in a Solar Array Drive Mechanism. Basic constructional details are shown in Fig. 1 from which it can be seen that the unit comprises identical Prime and Redundant motors.

On the Stator, each motor consists of a stack of corrosion resistant iron laminations carrying copper conductors in insulated slots. The Prime and Redundant windings are separated from each other at the closest point by means of a PTFE insulation ring. On the Rotor, each motor consists of a pair of Stainless steel pole pieces and a SmCo<sub>5</sub> magnet mounted on a common, non-magnetic shaft.

The motor has the following dimensions:

- Diameter                      57 mm
- Length                        76 mm
- Mass                           900 g

The basic performance of either the Prime or Redundant motors is:

- Holding Torque                                      .28 Nm
- Detent Torque                                        .07 Nm
- Power input for peak torque                      3.6 W
- D.C. Resistance                                    10.0  $\Omega$

Features of the motor include accurate alignment between Prime and Redundant motors to enable the use of either motor without significant loss of positional accuracy. This also enables both motors to be energised simultaneously to give approximately double the single motor torque if necessary. However, a disadvantage of aligning the motors in this way is that the detent torque also doubles, which reduces the overall torque capability of the motor. Had the requirement for accurate Prime and Redundant alignment not been a design criterion, it would have been possible to offset the Redundant motor by half a step from the Prime motor such that the Prime and Redundant detent torques would cancel leading to more useable driving torque.

The dynamic performance of the motor is shown in Fig. 2 where the pull-out torque (curve (a)) and the power input (curve (c)) are shown as a function of supply frequency. The drive used was full-step bipolar,



providing 600 mA maximum to either phase. The performance curves exhibit the usual frequency-dependent decrease of torque and input power which occurs with Stepping motors when the conduction period is short compared to the electrical time constant of the motor.

To simulate operation after one winding has developed a worst-case short-circuit failure, the leads from one phase of the redundant motor were connected together whilst the Prime motor was driven using the same drive as previously. Torque measurements made on the unit resulted in curve (b) shown in Fig. 2. It can be seen that the magnitude of the retarding torque (i.e. the difference between curves (a) and (b) is largely independent of supply frequency. This is attributed to the fact that Prime and Redundant windings share a common electrical time constant and thus the waveform of the fault current varies with time in the same way as the waveform of the supply current.

It should be observed that for any given frequency, the input power remains unchanged regardless of whether or not a fault is present on the Redundant winding. This is to be expected since the Prime and Redundant motors are electrically independent: the retarding torque of the failed motor is seen by the healthy motor purely as an increase in mechanical load.

#### Dual-wound Stepping Motor

This motor is a housed, size 23, 2 phase,  $1.8^\circ$  step motor designed for intermittent operation in an Antenna Pointing Mechanism. The rotor and stator assemblies are mechanically identical to either the Prime or Redundant element of the Tandem motor described above. The general arrangement is shown in Fig. 3. The Prime and Redundant windings are insulated from the stator stack by slot liners and from each other by Mylar slot dividers inserted between the two windings from either end of the stack. The two windings are thus physically separated from each other at all points.

The motor has the following dimensions:

- Diameter                    57 mm
- Length                     51 mm
- Mass                        620 g

The basic performance using either the Prime or Redundant winding is:

- Holding Torque                    .24 Nm
- Detent Torque                    .035 Nm
- Power input for peak torque       3.6 W
- D.C. Resistance                   17.0  $\Omega$

With both windings sharing a common stator stack, the changeover from one winding to the other can be accomplished without any variation in rotor position. This also means that both windings may be energised simultaneously to give increased torque capability. However, since this effect- ively doubles the power dissipation in the same stack, simultaneous operation should be performed with caution to avoid overheating the winding. Also, using both windings, it is easy to drive the magnetic circuit into saturation. Thus, rather less than double the torque is available; on the unit under consideration, an increase in Holding Torque of only 50 % is achieved with both windings energised.

The pull-out torque and power input characteristics of the motor are shown respectively, by curves (a) and (b) in Fig. 4. A full-step bipolar drive was used, providing up to 470mA to either phase. The winding on this motor is designed to provide approximately the same performance as for the Tandem motor for the same power input and this can be verified from the performance data.

To simulate a worst-case short-circuit fault, the leads from one phase of the Redundant winding were connected together whilst the Prime winding was driven as previously. Torque and input power measurements made on the unit gave the results indicated by curves (c) and (d) of Fig. 4. By comparing curves (a) and (c), it can be seen that the retarding torque due to the fault current is approximately 50% greater than for the Tandem motor and is frequency independent above 50 Hz. However, examination of curves (b) and (d) shows that the power input under fault conditions increases significantly as supply frequency increases.

Both the above effects are due to the inductive coupling between the Prime and Redundant windings; there is a significant transformer effect. At low frequencies (less than 25 Hz) electrical rise time is insignificant; the drive pulses are square waves and quasi D.C. conditions exist. There is little transformer action between the two windings and the fault current which flows is due only to the motion of the rotor. Power input under these conditions is the same as for no-fault conditions and the retarding torque is similar to that of the Tandem motor. At high frequencies (greater than 250 Hz) the transformer effect predominates. Current circulating in the failed winding acts to reduce the mutual flux density and this increases the difference between the emf induced in the Prime winding and the supply voltage. Hence the supply current and input power increase significantly and the additional fault current creates extra retarding torque. At intermediate frequencies, a combination of the two effects is present. The dual-wound Stepping motor is, therefore, very inefficient if operating at high speeds under fault conditions.

#### Dual-wound D.C. Motor

This motor is a housed, size 18, permanent magnet brush D.C. motor having redundant windings, brushes and commutators. It is designed for short term operations in a Deployment Mechanism. Constructional details are

shown in Fig. 6. The Redundant winding is fitted in the bottom of the armature slots, with connections brought out to the front commutator. The Prime winding is inserted on top of the Redundant winding and connected to the rear commutator. Within the armature stack, the windings are separated from each other and from the stack by Melinex insulators. Due to the large number of commutator connections which are required, it is not practical to separate the two windings in the overhang region at either end of the armature. The two sets of brushgear are supported by moulded plastic brushblocks.

The motor has the following dimensions:

- Diameter	44 mm
- Length	70 mm
- Mass	440 g

Using a 28 V supply, the performance using either Prime or Redundant windings is as follows:

Stall torque	58 Nmm	No-Load speed	6500 rev/min
Stall current	1.5 A	No-Load current	75 mA
Rated torque	12 Nmm	Torque constant	40 Nmm/A
Rated speed	5000 rev/min		

Due to the large difference between rated torque and stall torque it may well be necessary to operate using a current limited power supply to avoid damage to other parts of the mechanism. However, if this is not a constraint, then it is possible to energise both motor windings simultaneously to double the stall torque. On the particular motor under consideration, this could be achieved without saturating the magnetic circuit.

The application for this motor required it to be able to operate at very high armature temperatures. This, combined with the high rotational speed, gave concern over the integrity of the solder joints between the commutator and coil ends. However, failure of one or more of these joints would result in an open-circuit condition from which complete recovery is possible using the Redundant winding.

A short-circuit failure between two adjacent coils was simulated by connecting together two adjacent commutator segments on the unpowered winding. The resulting performance is shown by the dotted lines in Fig. 5. For any given output torque, the motor speed is decreased by approximately 12% from the no-fault value. Being a D.C. machine there is no transformer effect and fault current is entirely due to rotational emfs. Retarding torque, and hence additional input power, are therefore greatest at high speeds and zero at the stall point.

The same condition occurs in the event of a terminal-to-terminal short-

circuit, only here the effect is drastic with no-load speed reduced to less than 50% of the no-fault value. This is indicated by chain-dotted lines in Fig. 5. Fortunately, this could only result from a harness failure or other external fault.

## CONCLUSIONS

Although there are five basic types of redundancy at mechanism level, there are only three motor options: non-redundant, dual-wound or tandem. At motor level, non-redundancy gives smallest size, lowest mass and highest performance. At the other extreme, tandem motors can provide performance very close to that of non-redundant motors, but at the expense of almost doubling volume and mass.

An attempt has been made to compare the merits of the three types of redundancy and the results are shown in Table 1 for stepping motors and Table 2 for D.C. motors. It should be emphasised that the data given in the tables is intended for guideline purposes only. It is always necessary to consider specific requirements in detail to enable an optimum solution to be reached.

TABLE 1 COMPARISON OF REDUNDANCY METHODS FOR STEPPING MOTORS.

Motor parameter	Redundancy method		
	Non-redundant	Dual-wound	Tandem
Length	L	L	$L \times 1.9$
Diameter	D	D	D
Mass	M	M	$M \times 1.8$
<sup>a</sup> Holding Torque	$T_H$	$T_H \times 0.7$	$T_H$
<sup>a</sup> Detent Torque	$T_D$	$T_D$	$T_D \times 2$
<sup>b</sup> Effect of open circuit	-	No effect	No effect
<sup>b</sup> Effect of short circuit	-	Torque reduced as frequency increased	Reduced torque
Increase in input power due to short circuit	-	Power increased as frequency increased	None

- a. Comparisons made at same power input
- b. When fault occurs on unpowered winding

TABLE 2 COMPARISON OF REDUNDANCY METHODS FOR D.C. MOTORS.

Motor parameter	Type of redundancy		
	Non-redundant	Dual-wound	Tandem
Length	L	$L \times 1.2$	$L \times 1.9$
Diameter	D	D	D
Mass	M	$M \times 1.2$	$M \times 1.8$
<sup>a</sup> Stall Torque	T	$T \times 0.7$	T
<sup>a</sup> No-load speed	N	$N \times 1.4$	N
<sup>b</sup> Effect of open circuit	-	No degradation	
<sup>b</sup> Effect of short circuit	-	Operating speed reduced	
Increase in input power due to short circuit	-	Inversely speed dependent	

- a. Comparisons made at same power input at stall  
b. When fault occurs on unpowered winding.

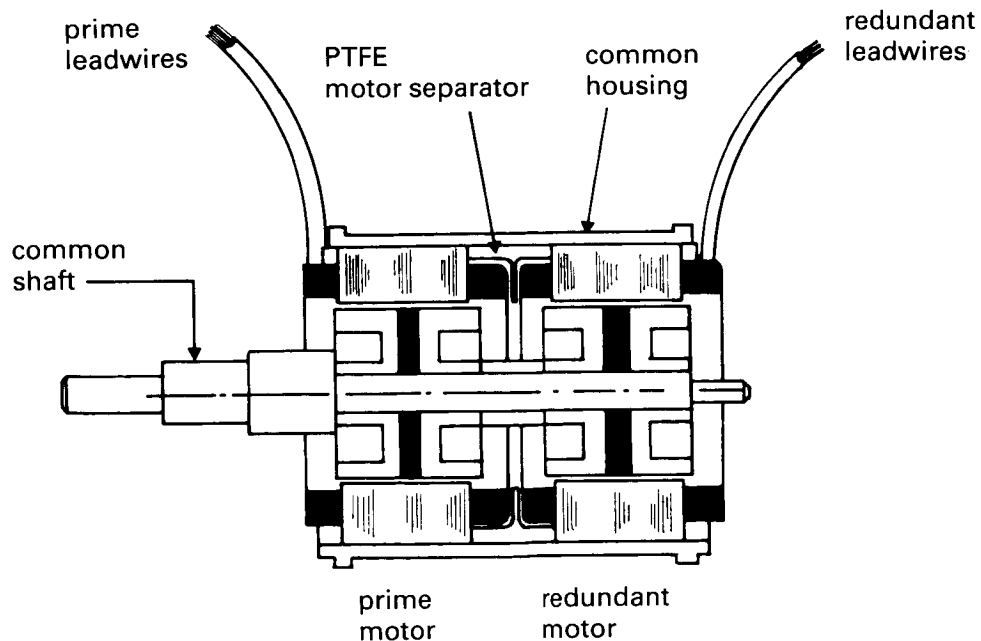


Figure 1. - Construction of tandem stepping motor.

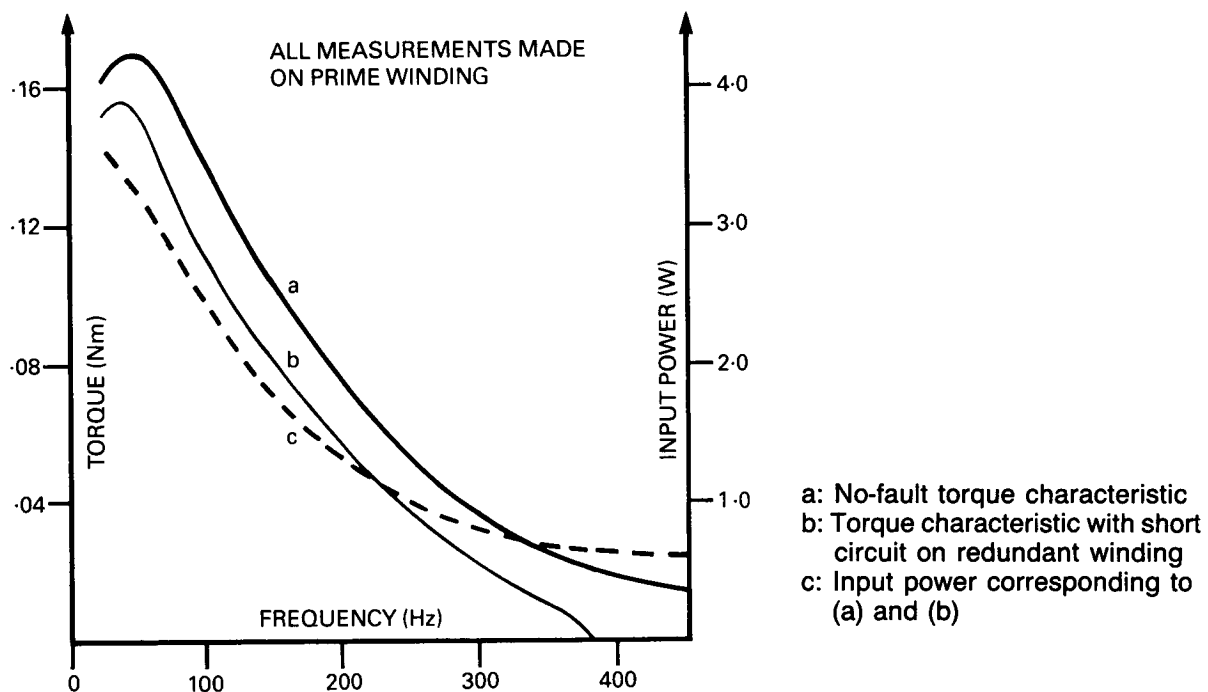


Figure 2. - Performance of tandem stepping motor.

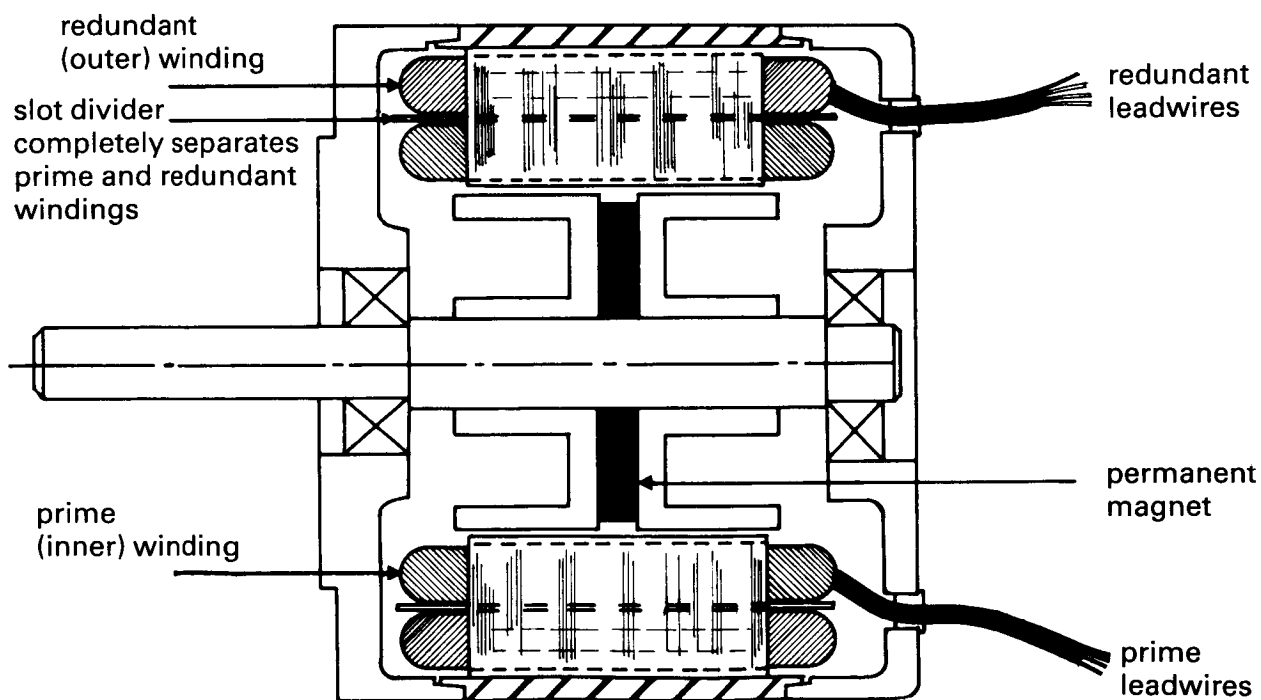


Figure 3. - Construction of dual-wound stepping motor.

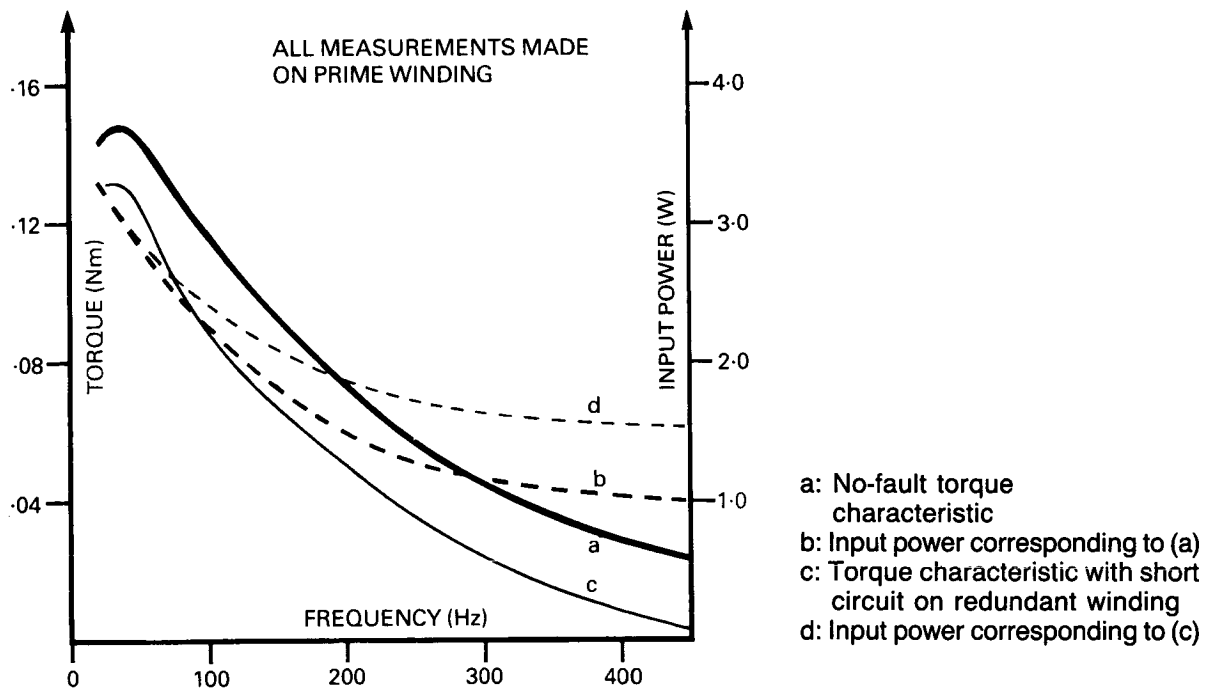


Figure 4. - Performance of dual-wound stepping motor.

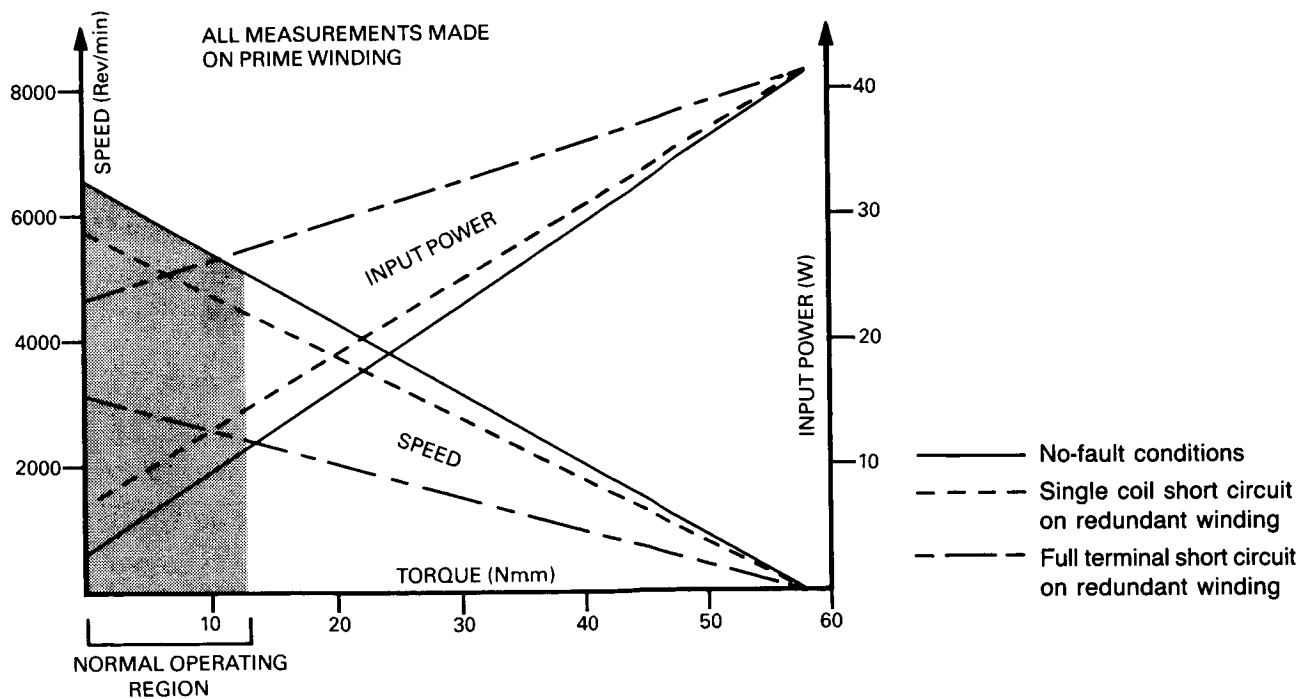


Figure 5. - Performance of dual-wound D.C. motor.

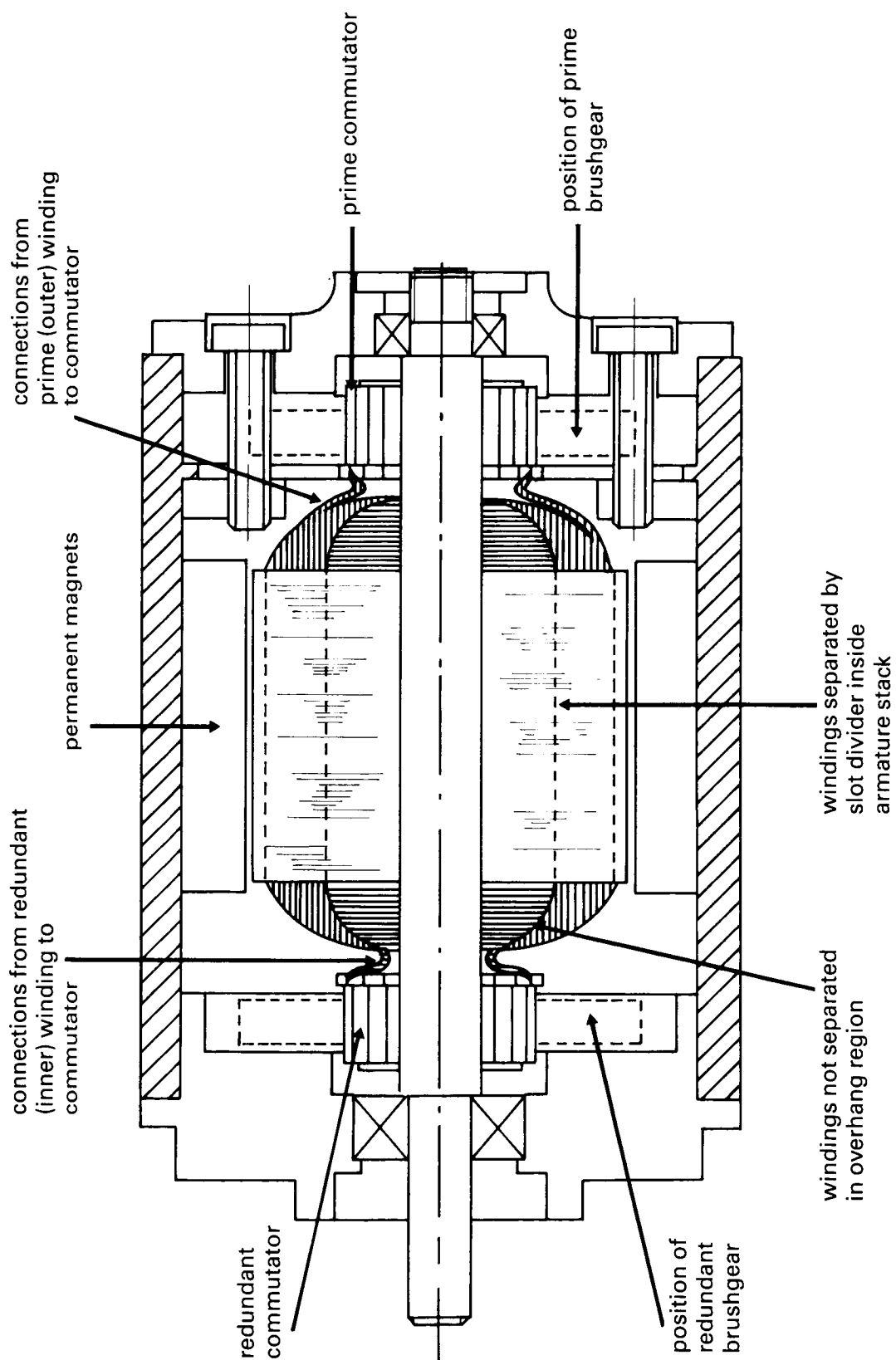


Figure 6. - Construction of dual-wound D.C. motor.